Micromanipulation and Micro-Assembly Systems.

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Abstract— **The needs to manipulate micrometer sized objects keeps growing and concerns numerous and various fields like microsystems (MEMS[1] and MOEMS[2]), micromechanics, optics, biology or pharmacy. The specificities of size, material, geometry and consistency of manipulated micro-objects, their surrounding, the kind of task to perform and the free size are all the more specific parameters that strongly influence the design and working of micromanipulation and micro-assembly systems.**

These systems are widely developing because they correspond both to industrial needs and really challenging scientific problematics. For these reasons, the present paper aimed at dealing with a review that mainly focuses on systems recently developed to assemble small series of microcomponents. The paper especially points out different solutions of carriers structures, gripping principles, sensors, other peri-microrobotic systems and control systems presenting the main solution and justifying their use and interest.

I. Introduction

In our everyday life, we are using more and more micro-sized products. A growing number of them requires to be manipulated or assembled (assembly sequence of 1 μm to 1 mm in size components) [1] [2] [3]. Applications include :

- the assembly of mechanisms (nanomotors, microgears, microball-bearings),
- the assembly of hybrid components (Micro-Opto-Electro-Mechanical-Systems, laser microsources, intelligent endoscopic capsules, mass microspectrometers),
- the assembly of optical systems (switches, connectors, assembly of lenses at the tip of optical fibers),
- the manipulation for biology needs (manipulation of cells, in vitro fertilization, study of the behaviour of bacterias),
- the manipulation for research needs (home made systems, spheres, fine salt grains, particules).

Fig. 1 displays examples of microcomponents requiring assembly.

Manipulation and assembly are extremely different problematic depending on whether we consider microscopic objects or millimeter sized objects [6] [7]. First of all the influence of adhesion phenomena caused by surface forces becomes prominent compared to volumic forces at the micro scale [8]. These forces act when two objects are in contact (contact between one manipulated object and an effector, the work plane or an other objet) but also at a distance. Thus, they cause lots of troubles for the taking or deposition of micro-objects. For this reason lots of research teams are working to understand, model and control adhesion forces [9] [10]. This step is necessary especially to automate micromanipulation tasks. Solutions either consist in reducing the bad effects of adhesion or using them advisedly.

[1]Micro-Electro-Mechanical Sytems
[2]Micro-Opto-Electro-Mechanical Sytems

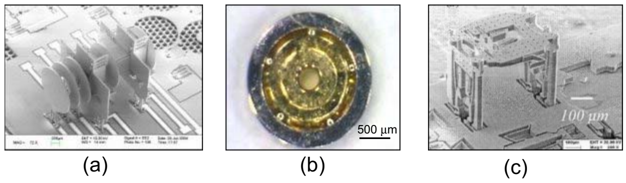

Fig. 1. Examples of assembled microcomponents: (a) small scale mass spectrometer [4] - (b) miniature ball bearing - (c) microconnector [5].

Moreover, micro-objects are generally fragile (small size, specific materials), requiring a control of the interaction forces during a micromanipulation task.

In the same way, the visual display has to be done using a system with a resolution compatible with the size of the manipulated objects. Optical microscopes and scanning electron microscopes are thus widespread. Applications in confined spaces require compact visualisation system such as fiberscope or microcamera.

Today, micro-assembly is mainly processed with high precision dedicated systems (expensive and low flexibility) or by hand by high skills technicians. Researches are under development to propose solutions as well for large series of products (parallel assembly [2] [11], self assembly [12] [13]) as for small series (serial assembly with robotic manipulators and microfactories) able to perform serial process with flexibility for small series.

The present paper is a review that mainly focus on systems currently used to assemble small series of microproducts. Most micromanipulation and micro-assembly systems are composed of a carrier, effectors, sensors, peri-microrobotic systems and control systems (Fig. 2). For this reason, section II aim at presenting carriers structures currently used. Gripping systems will be presented in section III. Sensors and other peripheral robotic systems will respectively be presented in sections IV and V.

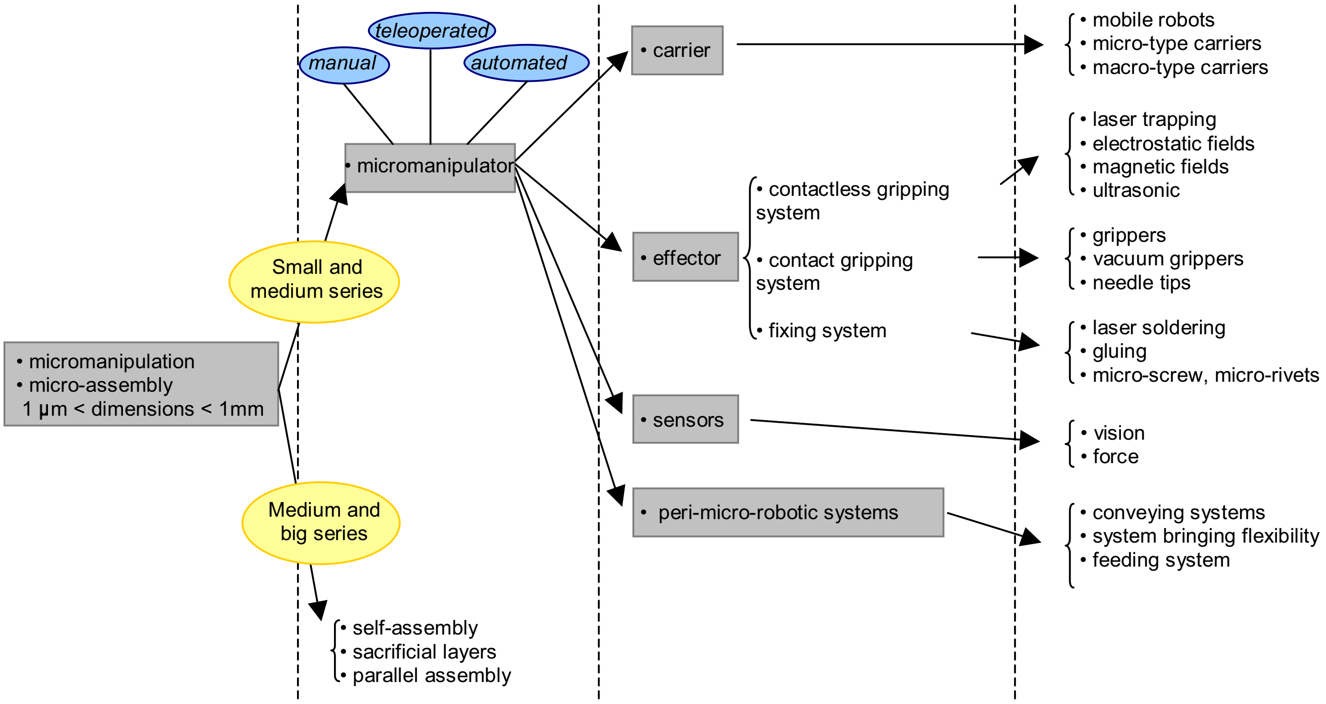

Fig. 2. System used to perform micromanipulation or micro-assembly tasks.

II. Carrier structures

Carrier structures permit to generate motions between an effector and a work plane (area where the objects to manipulate are placed). Depending on the application, the precision of positioning to achieve is comprised between 0,1 μm and 25 μm (Fig. 3). In general, strokes of a few centimeters range are enough. Thus, the manipulation of micro-objects require specific actuators and carrier structures. Most systems have either a serial structure or a distributed one and can be classified in mobile robot carriers, "macro"-type carriers and "micro"-type carriers. These three categories represent approximately and respectively 10 %, 40 % and 50 % of the systems presented in the literature.

A. Mobile robots

Mobile robots bring a high flexibility to perform micro-assembly tasks. They can be extremely compact and autonomous and several of them can be used at the same time, each being dedicated to perform one task (manipulation, visual display, fixing, conveyance). They can be used in different surroundings (air, vacuum) and their stroke are usually not limited [14] [15]. Their interest for being used to perform micro-assembly or in a microfactory is topical [16] [17]. Using mobile microrobots for micro-assembly needs is today mainly limited by their energy autonomy.

B. "Macro"-type carriers

"Macro"-type carriers are carriers that have been designed for "macro"assembly or precision assembly. They are usually bulky (from 50x50x50 cm^3 to several cubic meters) and their resolution is usually limited in the range of the tens of micrometers. For this reason, they are generally combined with high resolution/small strokes systems (piezo-actuated for instance). Thus, the resulting system take the advantage of the resolution of the fine positioning system and the high speed of the "macro"carrier. A relatively numerous systems using "macro"-type carriers have been developed. Indeed using carriers with well known characteristics and models is of great interest. Nevertheless, these systems suffer from the high influence of thermal expansion, inertia, overhang and low damping. Their size and the combination of several different action principles are other weak points.

C. "Micro"-type carriers

In the light of disadvantages of "macro"-type carriers, numerous research teams choose to design and study compact systems (stiffness, limited space surroundings) with dedicated actuators (strokes, precision). These "micro"-type carriers are generally a serial structure composed of elementary units, each generating one motion (translation or rotation). Some of these units are commercially available [18]. The main used actuators are piezoelectric, ultrasonic, based on an electromagnetic principle, DC motors or stepping motors. Some of them are capable of resolution much better than one tenth of microns. The main limitation of "micro"-type carriers are the speed generated and the difficulties to control them (behaviour highly not linear, robust control required).

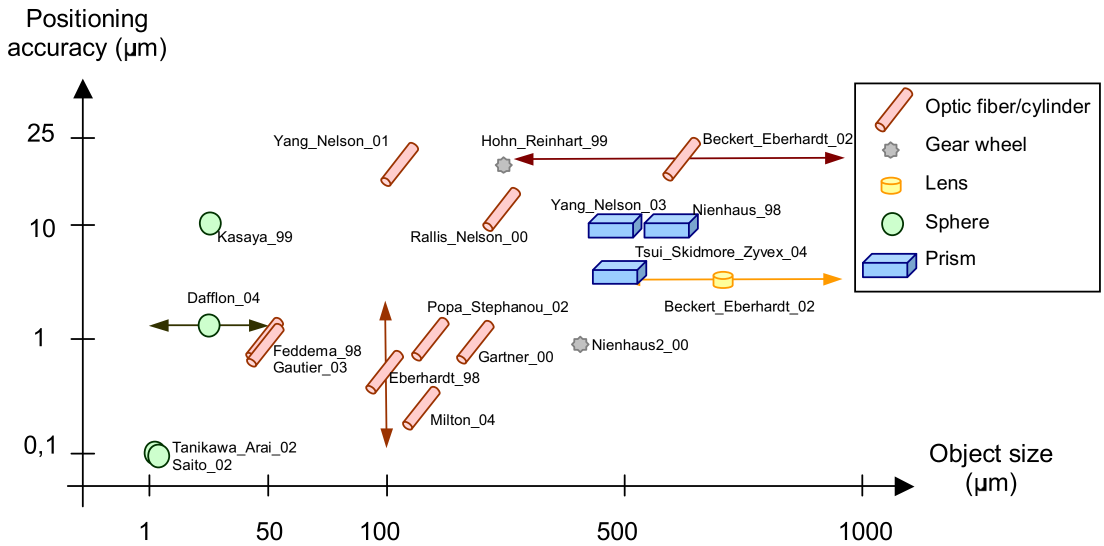

Fig. 3. Exemples of manipulated objects and precision of the micromanipulation task (necessary or performed in reality). The size taken into account is the diameter for optic fibers and the longer dimension for other components.

D. Conclusion about carriers

Carriers structures used for micromanipulation or micro-assembly needs have better to be compact for stiffness or size of surrounding reasons. Most micromanipulation stations are composed of one or two carrier structure, each having three (generally three translation XYZ) or four DOF -degrees of freedom- (translations XYZ and rotation of the work plane around Z). Except specific applications, like the fixation of a lens at the tip of an optic fiber that requires five DOF, today, few microcomponents require a micro-assembly system with more than four DOF.

III. Gripping systems

Up to now, huge works have been performed to propose various gripping principles and systems. The most widespread are grippers, needles, vacuum grippers or systems using adhesion phenomena. These gripping systems can be passive, active (with one or more degrees of freedom), equipped with sensors or compliant.

A. Microgrippers

Microgrippers are the most widespread systems used to grip micro-objects [19]. Their big advantage is that they enable to control the released position of an object when there is no adhesion problem. Most of microgrippers are composed of two fingers permitting a parallel gripping. Few grippers are passive, their working principle is based on bending beams [20]. Passive grippers are dedicated because their design is strongly linked to the characteristics of the manipulated objects. Moreover the object must be fixed on a support to permit the deposition.

The main part of microgrippers are active. Several action principle have been studied, the most used one are based on:

- piezoelectric elements that permit high resolutions, low response times but small strokes. To increase the effects of their strokes, piezoelectric elements can be stacked or can be included in an amplifying structure.
- shape memory allows that permit large strokes but suffer from being influenced by their surroundings. Moreover, they have a high response time and high hysteresis.
- fluidic actuated systems that are usually bistable and their use can be incompatible with fragile objects. Probably for this reason, they are generally limited to the manipulation of objects bigger than 500 μm.
- electrostatic systems that offers very weak strokes and forces. Moreover the motion generated can hardly be amplified. Their use is limited to smaller than 10 μm in size objects.

In the last past years, several multi degrees of freedom microgripper have been developed [21] [19]. In the same way, several systems using two independent perpendicular needles have been designed [22] [17] [23]. This dexterity brought at the tip of the manipulator enables to replace fine positioning systems currently used.

B. Vacuum grippers

Vacuum grippers are generally cheap and compact. They enable the manipulation of objects with various geometries, sizes and materials explaining why several teams use them [24] [25] [1]. Zesch et al. established that vacuum grippers can be used to manipulate 100 μm or more in size objects [26]. They experienced that this principle can even be used for random geometries of objects. Finally, the usefulness of using tools to guarantee the deposition in spite of adhesion effects has also been demonstrated (Fig. 4).

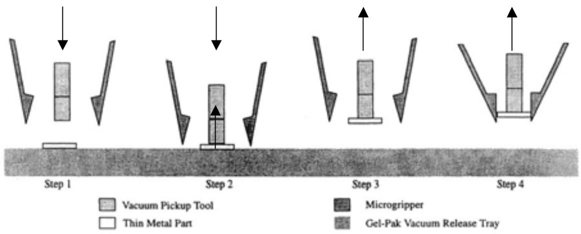

Fig. 4. Combination of two gripping system. A vacuum gripper enable the taking and transport of the object. The gripper is used for the deposition [27].

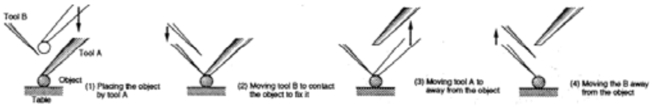

Fig. 5. Using two needles to pick and place an object [29].

C. Needles tips

Lots of research teams are working to understand adhesion effects that greatly modifies interaction forces at the microscale (difficulties to take one object among several, object stinking at the tool during the deposition phase, adhesion of two objets together). To perform efficiently micromanipulation tasks, the first solution consists in controlling the effects of adhesion forces. The surrounding itself can be controlled : for example a dry surrounding reduces a lot capillary forces [25]. In the same way, contact surfaces, materials, roughness and speed of the tool during the deposition plays a significant role during a manipulation process [28] [29] [30]. The second solution consists in using judiciously adhesion effects to manipulate micro-objects [9]. The most known principle consists in using a needle tip or an AFM (Atomic Force Microscope) tip [31]. To take an object of a substrate, adhesion forces acting between the tool and the object must be higher that forces between object and substrate. To guarantee the deposition, the opposite has to be performed.

These conflicting requirements cause numerous problems for the deposition. Nevertheless, it has been recently proved that considering a geometry of an object, it is possible to design a dedicated tool that simultaneously guarantees the taking and the deposition [9]. Other teams developed techniques to improve the effectiveness of the deposition phase, the following ones have been tested in automatic pick and place mode:

- using two tools with different size, one is used to pick the object, the smaller one is used for the deposition phase [29] (Fig. 5);
- using a technique of rotation of the tools permitting to modify the contact surface between the tool and the object [29] [32] (Fig. 6);
- using a trajectory of the tool during the deposition phase that is perpendicular to the normal of the contact between tool and object [33].

It is also possible to use capillary effects by trying to control a small quantity of liquid at the contact between a tool and

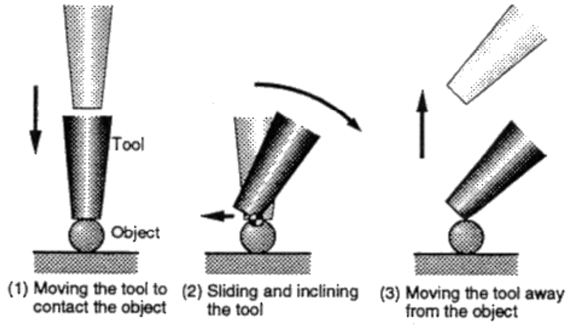

Fig. 6. Pick and place of a micro-object by rotation of the tool. It enables to control the surface of contact so adhesion forces between tool and object [29] [32].

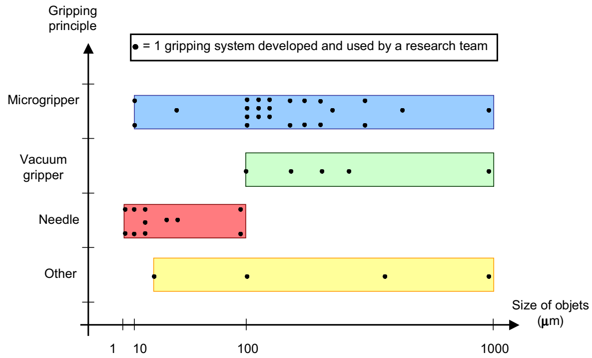

Fig. 7. Gripping systems used against the size of the manipulated objects. Each point corresponds to one system that has been used to experiment micromanipulation tasks.

the object. The control of the temperature permit to control the state of the water (liquid, solid and vapour) [30] [34] [35].

D. Other gripping systems

Specific applications led to the development of specific and dedicated tools. For example, a miniature lasso or a miniature shovel have been designed to manipulate protein crystals [36] [37].

E. Conclusion about gripping systems

To manipulate 1 μm to 1 mm in size objects several gripping systems can be used. Fig. 7 references the main systems used in the literature. This figure displays that their is a transition around 100 μm and that there is no universal gripping system. Works are done both to design grippers permitting the manipulation of objects smaller than one hundred of microns and for a better control of adhesion effects.

IV. Sensors

Sensors are essential to perform micromanipulation tasks in teleoperated mode but even more for systems aiming at working automatically. In this goal, the measure of force and position is a great challenge. Both of the kind of sensors must extremely precise and compact.

Force sensing aimed at preventing from damaging fragile parts (micro-object, accuracy of manipulators) but also to characterize adhesion forces. The former require a resolution in the range of hundreds of microNewtons whereas the latter a resolution of about 10 nN. Strain gauges are the most commonly used force sensors and enable to measure with 10 μN to 400 μN resolution in the range of 10 mN to 350 mN [32] [38]. Other principles were explored like a capacitance sensor [39] or a PVDF (piezoelectric polymer) [40] [41]. Up to now very few force sensors (compromise between resolution and size) have been developed for micromanipulation needs showing the difficulties of this problematic. Finally, adhesion forces are usually measured by an optical measure of the deflection of a bending beam [42] [43].

Vision systems cannot be overlooked to perform micromanipulation tasks even if they impress strong contraints (size, depth of field) due to the resolution required. They are generally used as a feedback for the positioning in two or three directions. Half micromanipulation stations have got only one vision system (from the top and perpendicular to the work plane in general). The other half of stations are equipped with at least two vison systems (one view from the top and one from the side). Optical microscopes is physically limited to the manipulation of objects bigger than 10 μm (for image processing). For smaller objects, it is usually required to perform the micromanipulation tasks inside the chamber of a scanning electron microscope (30 % of the cases). Vision systems compensate the lack of force sensors but are really bulky causing strong constraint about the design of micromanipulation systems. Very small cameras or endoscopic systems are really interesting in a size point of view but are today limited to the visualisation of more than 500 μm in size components

V. Other peri-microrobotic systems

Micro-assembly and more generally the development of a microfactory usually require peri-microrobotic systems. They are systems that are added to other systems presented up to now (carriers, gripping systems, sensors). Peri-microrobotic systems can be classified in three categories :

- feeding [44] and conveying systems (mobile robots [14], using palets [45] or based on guided wave propagation);
- temporary fixing systems like micro-vices and systems of tool changer that bring flexibility and compactness [46] [47];
- systems to control the quality of the tasks performed.

VI. Conclusion

Systems for manipulation and assembly of micrometer sizes components are living great developments. These systems can be classified in two categories: assembly of small series of products lead to flexible systems whereas large series corresponds to productivity, reliability and less toward flexibility. Assembly of small series of products generally require a carrier generating motions between effectors and the object to manipulate, effectors, sensors and peripheral systems. The

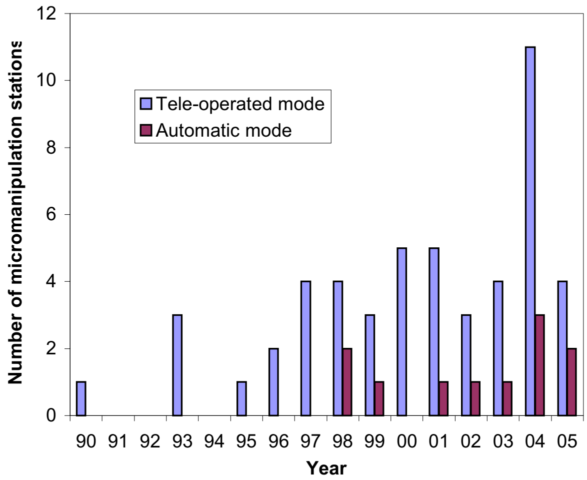

Fig. 8. Classification scheme of the micromanipulation stations in function of their mode of working. Only the micromanipulation station that have been used to perform a pick-transport-pose cycle of objects whose all dimensions are between 1 μm and 1 mm are taken into account.

global systems has to be compact, flexible and able to work automatically.

Compactness ensures precision of positioning (stiffness), reduction of energy consumption. Moreover such systems have often a small free space because of the really big size of vision systems or that they are either included in a microfactory or in the chamber of a scanning electron microscope.

Flexibility enables to perform successively different elementary tasks. Such systems are of great interest and economically attractive [48]. In the same way, modularity is necessary because it enables to change the structure of the micromanipulation system.

Finally, today, most micromanipulation tasks are performed in teleoperated mode. This principle brings a valuable help to operators. Automation of these systems mainly aims at a gain of cycle time, quality performed and constance of the production. Nevertheless, automation requires extremely precise sensors and particular robust control systems making the coming years particularly challenging.

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